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Insights into the Ocean Health Index for marine renewable energy

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ABSTRACT

Several nations around the world start to consider marine renewable energy (MRE) to be an alternative energy to sustainable development. The utilisation of the ocean includes common interests for food provision, artisanal fishing opportunity, natural products, carbon storage, coastal protection, tourism and recreation, coastal livelihoods and economies, sense of place, clean waters and biodiversity. An index is required to relate the marine renewable energy industry to ocean healthiness quantitatively. The Ocean Health Index (OHI) recently published in *Nature* measures the healthiness of the ocean within 171 Exclusive Economic Zones (EEZs). This study identified several data gaps and suggests improvements for the treatment of MRE in OHI calculations. It is suggested to include MRE effects under pressure (p_i) or resilience (r_i) variables based on the MRE technology type, stage of operation and its effects on OHI goals. The study suggests the OHI may be a suitable indicator to monitor MRE developments after fully including the components of MRE. Policy makers can use the improved OHI to balance the various multiple-competing activities in maritime spatial planning.

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1. Introduction

Marine renewable energy (MRE) can be harnessed through tidal barrages, marine currents, waves, thermal gradients and salinity gradients [1,2]. The ocean is source of marine renewable energy and it is equally important for food provision, artisanal fishing opportunity, natural products, carbon storage, coastal

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protection, tourism and recreation, coastal livelihoods and economies, sense of place, clean waters and biodiversity, as indicated in the recent paper of Halpern et al. [3] in *Nature*. Therefore, policy makers and scientists need an effective method to identify the balance of multiple competing activities that involve sharing the utilisation of the ocean and that potentially have conflicts with public interests [4,5]. Sustainable management of marine resource is required to control the excessive human activities and to maintain a healthy ocean ecosystem in various countries. Marine renewable energy is new compared to the list of industries used to determine the ocean health. This work looks into the composite index of ocean healthiness from the perspective of marine renewable energy.

Marine renewable energy extracts power from the ocean using tidal barrage [6,7], tidal current turbines [8,9], wave converters [10,11], salinity gradient converters [12,13] and ocean thermal converters [14,15]. Offshore tidal and wave farms are the new industries currently occupying the marine spaces. The United Kingdom has experienced challenges in policy making related to the boom in the marine renewable energy industry associated with the Orkney and Shetland archipelagos in the North Sea oilfields. Johnson et al. [16] stresses in his work on the benefits of granting special rights to country councils for managing the developments of the Orkney and Shetland archipelagos. Todd [17] discussed the reconciliation of large-scale marine renewable energy with other legitimate users of the sea. Those involved with fishing, ship navigation and recreation have the conventional right to use marine space. The marine renewable farm should not produce a negative impact on the existing users and communities. Energy policy in the UK encourages the development of the marine renewable energy industry. However, Alexander et al. [18] urged improvement in the marine policy in terms of a better consideration of all marine users. The fishing industry has expressed some concern over restriction to access and to navigate in MRE farms or adjacent areas. In a survey, most of the fishermen held either neutral or positive attitudes towards MRE development. Dolman and Simmond [19] recommended the Scottish Government should complete a full and transparent marine spatial plan before licensing the appropriate sites for marine renewable developments. The inclusion of cumulative impacts in all the multiple competing activities can predict the immediate, short-term and long-term effects.

As aforementioned discussion, policy makers require a quantitative index to aid in the decision making related to the marine spatial planning for marine renewable energy. MRE requires an index that projects its current status, economic benefits and environmental impact. However, no index has been found that assess the positive and negative impacts of MRE. The Environmental Performance Index (EPI) is an index used to identify environmental health and ecosystem vitality in a chosen country quantitatively [20]. The EPI has 25 indicators that cover climate change, forestry, fisheries, agriculture, water quality, air pollution, biodiversity and environmental burden of disease. However, an index that considers ocean health is more appropriate to assess marine activities. Therefore, the Ocean Health Index (OHI) is proposed for this purpose [3]. Unlike the EPI, the OHI considers only the ocean rather than both water and land bodies.

The Ocean Health Index considers both the balance of environmental performance and human's economic activities rather than the sole environmental concerns of the EPI. However, a few gaps have been identified in the OHI regarding the treatment of marine renewable energy. This work investigates and provides suggestions on how to further improve the Ocean Health Index from the perspective of marine renewable energy sector. Section 2 provides a brief overview of the OHI and its relationship with MRE. Section 3 presents current MRE systems and identifies data gaps in the OHI from the perspective of MRE. The manuscript concludes with a discussion section and suggesting the required improvements of the OHI to fully incorporate MRE.

2. Ocean Health Index

Halpern et al. [3] published a paper on the Ocean Health Index (OHI) in *Nature*. The OHI provides a direct measure of the healthiness of oceans. Tidal and wave energies in MRE have been included in Goal 7 of the ten goals (Table 1) used to define ocean healthiness. The driving force for the development of such index was the fact that human activities for economic purposes should not be stopped by the sole consideration of environmental impacts. Nevertheless, human activities can be limited with effective policy and proper marine spatial planning to provide a sustainable future.

The OHI aims to include a broad range of ocean activities for the benefit of sustainable management [3]. The OHI uses a quantitative method to measure and monitor the health of the coupled human–ocean system. This index consists of ten diversified public goals to calculate the index of each nation as shown in Table 1. The global index score of 60 out of 100 in year 2012 was used as a benchmark to compare among the various nations. The developed countries appear to perform better than the developing countries with a few exceptions.

2.1. Advantages of the OHI over other indices

Ecosystem health is defined as a human–nature coupled system. However, most assessments treat humans as a negative factor in the ecosystem [21]. The OHI couples human activity and nature to produce an indicator of ocean health. In doing so, the OHI considers both the pros and cons of human ocean activity. Similar to the EPI, Halpern et al. [3] developed a systematic

Table 1
Goals of the Ocean Health Index [3].

No.	Public goals of OHI
1	Food provision
2	Artisanal fishing opportunity
3	Natural products
4	Carbon storage
5	Coastal protection
6	Tourism and recreation
7	Coastal livelihoods and economies
8	Sense of place
9	Clean waters
10	Biodiversity

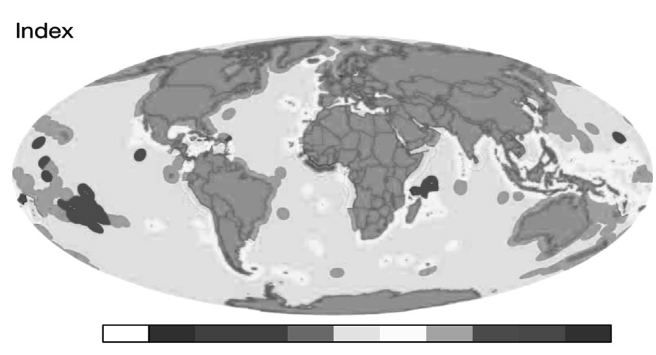

Fig. 1. Map of index scores per country [3]. Waters within 171 Exclusive Economic Zones (EEZs), up to 200 nautical miles, were assessed and are represented on the map.

approach to measure the overall condition of marine ecosystems. The OHI is a standardised, quantitative, transparent and scalable index. Policy makers, scientists, managers and the public can use the OHI to better understand ocean status [3]. Fig. 1 shows the OHI scores throughout the world.

2.2. Formation of the OHI

The index (I) score is a weighted sum of the ten goal specific index scores (I_i) represented in Eq. (1).

$$I = \sum_{i}^{N} \alpha_i I_i \tag{1}$$

where α_i is weightage for each goal, and I_i is the average present value and likely future status for each goal i.

The OHI framework was used to calculate the index score of each goal and sub-goals. The framework is shown in Fig. 2. The tracking of individual components and combining of each component are equally important for the direct comparison of management objectives. Therefore, a robust framework was used to assess the ocean health and to motivate data collection to strengthen the future improvement of the index. Index (I) consists of four dimensions: current status, trend, pressures and resilience. The framework uses trend, pressures and resilience to calculate the near-future status for each goal. A set of data layers is used to represent the current status of each goal with respect to the calibrated reference point.

The index (I_i) for each goal and sub-goal is calculated using Eq. (2).

$$I_i = x_i + x_{I,F} \tag{2}$$

Index (I_i) is a function of the present status, x_i and the near-future status, $x_{I,F}$ as shown in Eq. (3). The estimation of the near future status, $x_{I,F}$ is based on three parameters that are the recent trend (T_i), pressure (p_i) and resilience (r_i).

$$x_{I,F} = (1+\delta)^{-1}[1+\beta T_i + (1-\beta)(r_i - p_i)]x_i \tag{3}$$

where δ is the discount rate and β is the weightage for trend (T_i).

The parameters of pressure (p_i) and resilience (r_i) are included in the calculation of near future status of each goal. The negative effect of human or ecological factors on a goal is called pressure, whereas the positive effect on a goal is called resilience. The present status and recent trend indicate the direction and rate of change based on available data. It is recommended that interested parties read the OHI paper from *Nature* to further understand the methodology. Supplementary documents are available based on requests describing the OHI methodology, results and discussions in depth [3].

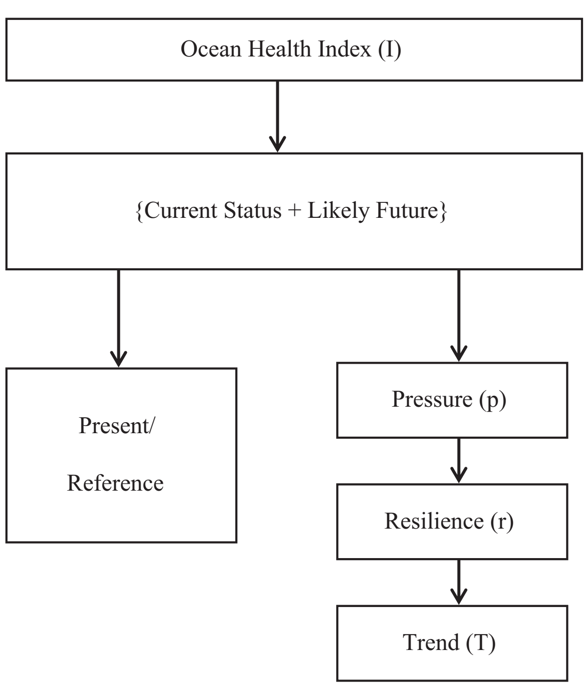

Fig. 2. Framework of OHI and components [3].

2.3. MRE components in the OHI

Two sets of MRE data layers have been used to calculate this index. They consist of two sub-goals, including the livelihoods and economies. The marine jobs data from the tidal energy sector; and marine revenue generated from electricity production was used in the OHI calculation.

2.3.1. Value of MRE for job opportunity and revenue

The total value of coastal economic industries cannot be fully understood by only considering the jobs and revenue generated directly from those industries. Trend in direct industry stimulated additional jobs and revenue generated indirectly from the related industries [3]. For example, the marine industry provides direct jobs to engineers and workers, but it also produces indirect jobs to the turbine manufacturers, restaurants and cinema theatres where these employees spend their income. The index uses a set of sector specific multipliers to calculate total jobs or revenue impacts as shown in Table 2. Wave and tidal energy have high job and revenue trends with high multipliers. The aim of the goal is to avoid loss of coastal and marine-dependent livelihoods and maximise coastal economies (revenue). Tidal and wave energy has been found to contribute to both the jobs and economies of coastal areas.

2.3.2. Inconsistency in OHI data

The OHI has only collected data from tidal and wave energies to produce an index for goal coastal livelihoods and economies [3]. As noted in the introduction, marine renewable energy consists of tidal barrages, marine currents, waves, thermal gradients and salinity gradients. Only the data from La Rance and Annapolis plants were used in index published for the year 2012. The consideration of MRE in the OHI with only two tidal barrages may be insufficient to reflect the reality of MRE. Section 3 discusses the various commercial MRE plants in the world. These plants should have been included but were found missing.

Nevertheless, MRE needs an index that helps policy makers and scientists in making the best use of marine resources globally for electricity generation. The OHI can be considered as the best candidate to monitor the balance between the marine renewable energy development in terms of economy benefit and environmental protection.

Table 2
Sector-specific multipliers used to calculate total jobs and total revenue [3].

Sector	Jobs	Revenue
Wave and tidal energy	1.88	1.652
Marine mammal watching	1.915	1.0
Aquarium fishing	N/A	1.568
Commercial fishing	1.582	1.568
Mariculture	2.7	2.377
Tourism	N/A	N/A

3. Current status and recent development of MRE

Interaction between the earth and planetary forces gives rise to tides in the ocean. The temperature difference produces wind, and the wind transfers the kinetic energy forming the oceanic waves. Ocean covers 70% of the earth surface as the largest receptor of thermal energy from sun. The evaporation from the ocean surface gives rise to the salinity differences between the ocean water and river water. The sources of marine renewable energy include tidal ranges, tidal currents, ocean waves, ocean thermal gradients and salinity gradients. A wide range of technologies are used to harness various types of ocean energy through tidal barrages, tidal

Fig. 3. Shihwa power plant [22].

Fig. 4. SeaGen tidal turbine of MCT (Marine Current Turbine Ltd.).

Table 3
List of world-wide commercial MRE power plants.

MRE power plant	Capacity (MW)	Country	Year of Commission
Shihwa Lake tidal barrage	254	South Korea	2011
WaveDragon	1.5	Denmark	2011
Uldolmok Tidal Station	1.5	South Korea	2009
SeaGen	1.2	Ireland	2008
Annapolis Royal Generating Station	20	Canada	1984
Jiangxia Tidal Power Station	3.2	China	1980
Kislaya Guba Tidal Power Station	1.7	Russia	1968
La Rance Tidal Power Station	240	France	1966

turbines, wave converters, OTEC (Ocean Thermal Energy Converters) and salinity gradient devices.

Tidal barrage is the most established technology among the five types of MRE. Tidal and wave energies have also made significant progress in the past few decades, enabling the research and installation of tidal and wave farms at various sites around the world. The Shihwa Lake tidal barrage in South Korea is the world's largest barrage with a capacity of 254 MW [22], as shown in Fig. 3. La Rance is the oldest and the second largest tidal barrage with a capacity of 240 MW [2]. Annapolis is the third largest tidal barrage in the Bay of Fundy, Canada. The Annapolis tidal barrage has a power capacity of 20 MW. SeaGen is the world's first commercial tidal current turbine in operation at Strangford Lough, Northern Ireland (Fig. 4). The capacity of power generation for SeaGen is 1.2 MW. WaveDragon is the first commercial wave power plant in the world. It is located at the North Sea Demonstrator (Denmark) with a power capacity of 1.5 MW [2].

As seen in Section 2.3.2, the OHI considered only two power plants of La Rance and Annapolis plants. However, eight commercial power plants have been identified as being operational. The various MRE plants in operation are listed in Table 3. OTEC and salinity gradient technology are catching up fast and are likely to start operation at the commercial level in coming years. The IHI Plant Construction Corporation, Xenesys Incorporation and Yokogawa Electric Corporation are working together to build a trial OTEC plant in Japan [2].

4. Discussion

In introduction, the need for a global index that reflects the healthiness of MRE has been presented. Introductory and later sections indicated that the OHI is closest for MRE. Sections 2 and 3 critically analysed the OHI components and latest developments in the MRE sector. Some inconsistencies in MRE data points were found in the present OHI index. MRE consists of five major technologies: tidal barrages, marine currents, waves, ocean thermal converters and salinity gradients. The OHI implements the MRE data under the category “tidal and wave energy”. Tidal and wave energies are the most established among the five types of marine renewable energy, and tidal energy is in the commercial stage. However, the data from only two power plants (La Rance and Annapolis Royal plants) were collected for the calculation [3]. Both the plants are tidal barrage-type power plants, and the tidal current energy has not been considered. Therefore, data from the tidal current energy, wave power, OTEC and salinity gradient power are required to fully include MRE in the OHI. Table 3 shows eight commercial plants around the world, but the OHI relies only on collected data for two power plants. Thus, data collection improvement is required to better reflect the condition of the marine renewable energy industry.

4.1. Suggestions for improving the Ocean Health Index

As discussed in Section 2.3, the OHI takes into account data collected on marine jobs and marine revenue generated in the MRE sector. However, a later study, discussed in Sections 4.2 and 4.3, indicates that MRE can have positive or negative effects on the health of ocean, and MRE may not be contributing only to the economy and power sector. Therefore, the following suggestions are provided to further improve and to incorporate MRE in the OHI. Sections 4.3 and 4.4 give detail considerations of physical features and type of MRE systems in the OHI calculations.

4.1.1. Data collection of marine renewable energy

Data collection of tidal barrage, wave energy and tidal current energy need to be included in the data layers of jobs and revenue. Other technologies under MRE create jobs opportunities in research and lead to allocation of huge government grants to push forward the development. The OTEC and salinity gradient power can create jobs, both in terms of installation and tourism. Thus, use of the term MRE instead of the “tidal and wave energy” sector is more appropriate in the index. The comprehensive inclusion of the MRE technologies and data from more plants are required to produce a more accurate index.

4.1.2. Effect of MRE on goals of the OHI

Previous studies have demonstrated the impacts of MRE on the fish population, regional species, migrating birds, mammals, diving birds, tidal heights, sedimentation pattern, habitat of sea species, large scale orientation, feeding or mate finding, algal growth and ship transportation. Kirshvink [23], Neill et al. [24], Desholm and Kahlert [25], Wilson et al. [26], Goss-Custard et al. [27], Harrison [28] and Langton et al. [29] examined these effects of MRE on ocean health. Thus, MRE devices have impacts on the goals of OHI, such as biodiversity, food provision and artisanal fishing opportunity.

Neill et al. [24] concludes the impact of tidal stream turbines on the sedimentation dynamics. Tidal current turbines, when placed in a region of high tidal currents, alter the hydrodynamics of the tidal region, which is analogous to increasing bed friction. Numerical simulations indicate that the energy extracted from regions of strong asymmetry has significant effect on sedimentation dynamics compared with the symmetric region [24]. Therefore, MRE should be included in other nine goals and not only Goal 7, “coastal livelihood and economies”.

La Rance is the oldest tidal power plant and has offered its data since 1966. The data describe the economic benefits and the environmental impacts to the surrounding ecosystem. La Rance has a total installed capacity of 240 MW. This implies that much less fossil fuel has been used since its commissioning. The operation and routine maintenance of the plant provides employment for up to 28 staff members and over 70,000 tourist visit

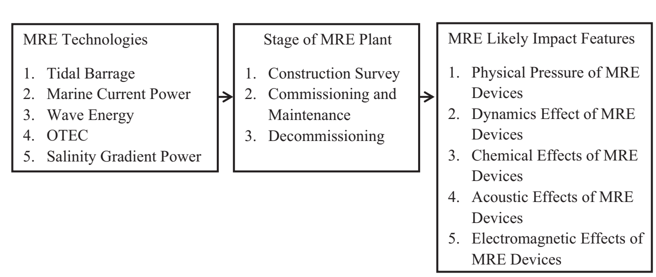

Fig. 5. MRE and its components that impact OHI goals.

every year [30]. The tourism industry provides good employment opportunities to the local communities. Thus, a marine renewable plant provides green energy, livelihood and economy development for the region and country. The environment is healthy, but it may change the ecosystem. The barrage has led to the limited silting of the ecosystem. Sand-eels and plaice populations have declined near the barrage, and sea bass and cuttlefish have returned to rivers. The mean water level in the lagoon has increased to a higher level compared with before construction. The sedimentation pattern has been changed, leading to the decrease in the tidal range in La Rance [30]. Therefore, the economic benefits and ecological impacts should be taken together into account as effects of MRE on ocean health.

4.1.3. Various stages of MRE development and environmental impacts

As an initial indicator, the authors suggest incorporating MRE effects into the goals of the OHI. Boehlert and Gill [31] concluded that the impact of the various MRE technologies may not be the same, and the magnitude of the impact may also be different at various stages of development, including the construction, commissioning and decommissioning stages. In the OHI calculation, the environmental impact of MRE should be included in a much broader sense rather than only during the commissioning phase. Secondly, the impact of a MRE power plant on the other goals such as biodiversity, food provision, natural products and coastal protection must be considered in terms of resilience (r_i) or pressure (p_i) terms.

The OHI index aims to make sustainable exploitation of a marine resource by incorporating or suggesting changes to the required data for each goal. The index framework uses two variables, resilience (r_i) and pressure (p_i), for calculating the near-future score of the goals. Resilience is defined as the social, institutional and ecological factors that positively affect the ability of a goal to be achieved. Therefore, any impact of MRE that is positive should be listed under resilience, such as habitat improvement and the increase in fish stock near MRE farms.

Pressure is defined as anthropogenic stressors that negatively affect the ability of a goal to be achieved. Therefore, any impact of MRE that is negative should be listed under pressure, such as the reduction of regional species, effect on migrating birds, ship transportation, and reduction in tidal height and the change in sedimentation pattern. Components of MRE and various stages of its development that affect other goals of OHI are shown in Fig. 5. These should be used to identify the variables of resilience (r_i) and pressure (p_i) for calculating the near-future score of goals. The next section suggests criteria for choosing the effects based on previous findings in the MRE sector.

4.2. Operational stages of MRE power plant

This section highlights various development stages a MRE power plant needs to go through and their effect on OHI goals, which vary with time. The impacts are discussed under three sets: (1) operational stage of MRE power plant, (2) physical features of MRE and (3) type of MRE. Table 4 provides a comprehensive list of MRE impacts.

A MRE power plant requires survey, construction, commissioning and decommissioning. The purpose of the survey stage is to select and to study the suitable location for construction of the MRE plant. The ideal site should normally be environmental friendly with no significant effect on the fish population, coastal protection or other goals of the index. The construction stage involves the process of building the new structures, installation and the removal of natural structures. This stage involves different heavy machinery that produces noise during operations. The noise has demonstrated to have a negative impact on fish prey and predator relationships [38,40]. The construction stage reduces the amount of fisheries around the plant location. Thus, it may have a temporary impact on biodiversity and food provision. The commissioning of the plant will have a long-term impact, unlike the problems in the construction stage.

4.3. Resilience, pressure and physical features of MRE plants

The physical features of MRE plants, such as physical presence of devices, chemicals, acoustics and Electro Magnetic Fields (EMF) generation, have been demonstrated to have effects on the sea environment [32–39]. Devices that have moving parts, such as turbine blades can cause blade strikes due to its high blade tip velocity [26]. MRE structures cause blockage to the natural flow of the marine current and waves, causing scouring effects and

Table 4
Impact of different types of MRE on the environment and humans

	Tidal energy	Wave energy	OTEC	Salinity gradient
Physical presence of device	Physical barriers to migratory species. [32]	Artificial habitat for different organisms, attracts pelagic organisms, providing fish aggregation [33,34]	Large pipes extend to deep sea, new habitat for species (creating reef effect)	
Dynamics effects of devices and energy removal effects	Turbine blade strike due to high tip velocity (danger to diving birds and fishes) [26] Blockage to turbulent and natural flow cause changes to benthic sediment scouring and alteration of sediment transportation [35]	Restricts vertical movement of organisms, prey and predator aggregation. Restriction of shipping lanes (transportation)	Effects not known	
Chemical	Potential spill of hydraulic fluid and leaching of anti-fouling plants	Potential spill of hydraulic fluid and leaching of anti-fouling plants	Potential spill of ammonia highly dangerous to fishes and leaching of anti-fouling paints [36]	
Acoustic	Noise has effects on sea animal communication, reproduction, orientation, and prey and predator sensing [37,38]	Noise has effects on sea animal communication, reproduction, orientation, and prey and predator sensing [37,38]		
Electro-Magnetic Fields (EMF)	Localised EMFs created around cables transiting electricity have effect on migrating sea species [39]	Localised EMFs created around cables transiting electricity have effect on migrating sea species [23,39]		Same as other technologies
Physical presence of device	Physical barriers to migratory species [32]	Artificial habitat for different organisms, attracts pelagic organisms providing fish aggregation[33,34]	Large pipes extend to deep sea, new habitat for species (creating reef effect)	

alteration of sedimentation process [24]. The physical presence of devices also reduces the free passage of commercial ships. The chemical impact is minimal, but the potential spillage of the hydraulic fluids can cause mass damage to fish and other sea species [35]. The leaching of anti-fouling paints can also lead to degradation of the sea environment. OTEC plants have been demonstrated to have the highest potential to damage the fish population in case of accidents, as ammonia is a popular working fluid for these type of facilities. MRE devices, over the long-term, can act as fish aggregation devices, which leads to increases in fish stocks [33,34]. However, the potential fishing area is reduced because of the presence of the devices. Thus, the OHI goal "food provision" is affected by MRE plants and devices. The EMF generated by the long electric cables used to carry the power to shore have demonstrated effects on migrating species.

Thus, the impact due to the physical presence of the plant devices, EMFs and acoustics need to be considered in terms of resilience or pressure for the calculation of the OHI index. Precautions need to be taken when including impact under pressure (p_i) or resilience (r_i). The resilience and pressure parameters of MRE have to be specific to the operating device and location. The generalisations of MRE impact on the environment will incorrect OHI calculations.

5. Conclusions

MRE technologies have enormous potential as an energy source. Initiatives such as the US National Policy and EU Maritime Strategy have been developed to make the comprehensive use of marine-ecosystem for the benefit of both humans and nature. The sustainable delivery of ten marine goals is the foundation of the OHI calculation. The OHI can be used for MRE as an index to aid policy making. MRE data were used in the calculation of index for a goal, i.e., coastal livelihood and economies. The data collected from the MRE sector in the index includes two power plants: Annapolis and La Rance. However, 80% of commercial MRE plant data were not previously included. Therefore, data collection needs to be improved for index calculation with respect to MRE.

Suggestions for fully incorporating the MRE sector into the OHI calculation have been discussed. MRE has both positive and negative impacts on the other nine goals of the index. Therefore, it is suggested to include these effects under the variables of pressure (p_i) or resilience (r_i) in Eq. (3). The impact of MRE plants and devices may fall under resilience or pressure. Suitable criteria for this selection were identified based on the type of MRE technology, stage of operation and their effects on the goals of the OHI. The term used in Halpern et al.'s [3] work for the MRE sector is "tidal and wave energy", which does not comprehensively capture all MRE technologies. Therefore, the term of "tidal and wave energy" sector should be modified to marine renewable energy (MRE). This can better describe the current and future marine energy technologies. This index represents the ocean's benefits to humans and negative effects to ocean because of human activity. The index is an important step toward improved policy making for equally competing and conflicting marine activities. The future of marine resource usage should be transparent and based on a policy of balanced usage for all marine sectors.

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